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PERFORMANCE OF SEVERAL CAST NICKEL-BASE ALLOYS AS TURBOJET-ENGINE BUCKET MATERIALS AT 1650° F

By James R. Johnston, Charles A. Gyorgak, and John H. Sinclair

Lewis Research Center
Cleveland, Ohio

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SUMMARY

An investigation was conducted to determine the times to failure and the types of failure of nickel-base alloy buckets in a modified J33 engine, with the midspan bucket temperature maintained at 1650° F (turbine-inlet temperature, 1800° F). The materials investigated included Inconel 713, Udimet 500, Guy alloy, and F-342, obtained from various commercial sources, and an early experimental NASA alloy cast at the Lewis Research Center. The engine was operated under cyclic conditions in which each cycle consisted of 5 minutes at idle (4000 rpm) followed by 15 minutes at rated speed (11,500 rpm).

During the engine test 70 percent of the buckets developed thermal-fatigue cracks on the leading edge. These cracks were observed on buckets of some alloy groups after 21 hours and in all groups after 154 hours. The median bucket fracture life ranged from 90 to over 407 hours at rated-speed conditions. The bucket lives, obtained in the J33 engine at a bucket temperature of 1650° F, are comparable to those of more conventionally used bucket alloys in the same engine at 1500° F. The shortest median fracture life was obtained with argon-cast Udimet 500. Inconel 713 and the NASA alloy had median fracture lives greater than 407 hours, the time at which the test was terminated. In each case where the median fracture life could be determined, it was well below the expected life based on material stress-rupture properties. While two-thirds of the bucket fractures were of the stress-rupture type, the remainder contained visible evidence of mechanical fatigue. A comparison of the results obtained with vacuum-cast and argon-cast Udimet 500 buckets indicated that the performance of the vacuum-cast group was superior on the basis of median fracture life (130 against 90 hr) as well as median time to thermal-fatigue cracking (over 109 against 21 hr).

INTRODUCTION

In recent years, significant advances have been made in the development of materials for high-temperature applications. Increases in the high-temperature strength of cast nickel-base alloys have been attained through alloy development and improvements in melting and casting procedures. In view of the desirability of increasing turbine-inlet temperatures to improve turbojet engine performance such cast alloys warrant increasing consideration for turbine-bucket materials.

Although many nickel-base alloys show definite potential at advanced temperatures on the basis of strength, their selection for turbine-bucket materials also depends on adequate fatigue strength, corrosion resistance, and satisfactory resistance to impact damage. The suitability of these alloys for bucket materials can best be determined by actual operation in full-scale turbojet engines.

Several of the stronger commercial and experimental nickel-base alloys have been investigated previously in turbojet engines at advanced turbine-inlet temperatures at the NASA Lewis Research Center. Inconel 713, Udimet 500, Sel-1, and B and B alloys were investigated as bucket materials in a J47 engine modified for operation at a midspan bucket temperature of 1700° F (turbine-inlet temperature, 1850° F) (refs. 1 and 2). In this engine, the buckets were subjected to a relatively low centrifugal stress, approximately 11,000 pounds per square inch near the midspan where the 1700° F bucket temperature occurred. The results of these tests indicate that all the alloys possess definite potential as bucket materials at this temperature and stress condition, although considerable thermal-fatigue cracking was encountered with each alloy. Another investigation (ref. 3) was conducted with argon-cast Guy alloy buckets in a J33 engine modified for operation at a midspan bucket temperature of 1650° F (turbine-inlet temperature, 1800° F). In this engine, the buckets were subjected to a considerably higher centrifugal stress (19,000 psi) in the midspan region where the 1650° F bucket temperature occurred. Although this test was terminated prematurely because of a compressor failure, the accumulated rated-speed time of 102 hours, without any bucket failures, indicated that argon-cast Guy alloy also had considerable potential for advanced-temperature turbine-bucket applications.

The present investigation is a continuation of these studies at advanced turbine-inlet temperatures and bucket centrifugal stresses on the order of 20,000 pounds per square inch. The alloys considered in this investigation were Inconel 713, Udimet 500, Guy alloy, F-342, and an early experimental NASA alloy. More recent developments in cast nickel-base alloys have demonstrated still higher elevated temperature strength characteristics; nevertheless, it is believed that the alloys selected for this investigation can provide a useful indication of the potential of this class of materials for advanced-temperature turbine-bucket applications.

The primary objective of this investigation was to determine the times to failure and the types of failure of turbine buckets cast from these materials in a J33 engine modified to provide a midspan bucket temperature of 1650° F (turbine-inlet temperature, 1800° F). The buckets of the different alloys were obtained from several commercial sources, and various casting procedures were employed. Only in the case of the Udimet 500 alloy were both a vacuum-cast and an argon-cast group of buckets obtained from the same master heat; thus, a comparison of the relative performance of vacuum-cast and argon-cast Udimet 500 buckets could be made. This comparison was considered to be a secondary objective.

The engine was operated for repeated cycles of 5 minutes at idle (4000 rpm) and 15 minutes at rated speed (11,500 rpm); operation was terminated after 407 hours at rated speed. Bucket elongation measurements were made at periodic intervals during the test, and the buckets were subjected to macroscopic inspection and metallographic examination before and after operation.

APPARATUS, MATERIALS, AND PROCEDURE

Test Engine

The engine used in this investigation was a conventional J33-9 turbojet modified to permit sustained operation with a midspan bucket temperature of 1650° F. The major modification consisted of introducing bleedoff ports between the diffuser section and the combustion chambers. By extracting 3 percent of the compressor airflow through these ports, it was possible to operate the engine at the higher temperature level without causing compressor surge. Also, an S-816 alloy turbine disk was substituted for the standard 16-25-6 alloy disk to preclude the need for disk cooling.

Turbine Buckets

Investment-cast buckets of Udimet 500, Inconel 713, F-342, and Guy alloy were obtained from commercial sources, while buckets of an early NASA experimental alloy (ref. 4) were investment cast at the Lewis Research Center. The nominal chemical compositions of these alloys are given in table I. The number of buckets of each group tested and pertinent casting information are given in table II. The two groups of Udimet 500 buckets were obtained from a single vacuum-melted master heat. All buckets were tested in the as-cast condition. Before engine testing, the buckets were inspected with radiographic and fluorescent-dye penetrant methods. The commercially cast buckets were required to be free from defects detectable by X-ray inspection but were allowed to contain some small surface defects in the central portion of the airfoil and in the base. The NASA alloy buckets had rather severe surface defects over the major portion of the airfoil, and several had internal casting defects. It was necessary to use these castings, which represented an initial attempt to cast buckets of this alloy, to meet the engine test schedule. Spare buckets of several alloys were procured for use as replacements for buckets that fractured during the test.

Engine Operation

Fifty-two test buckets and two thermocoupled buckets were installed in a J33-9 turbojet engine. The engine was operated for repeated cycles of 5 minutes at idle (4000 rpm) and 15 minutes at rated speed (11,500 rpm). Only time accumulated at rated speed is considered in discussions of bucket performance. During the rated-speed portion of each cycle, the midspan, midchord temperature of the buckets was monitored with thermocouples mounted in two S-816 buckets (shortened to reduce centrifugal stress). The midspan bucket temperature was maintained at 1650° F by adjusting the exhaust-nozzle opening. The rated-speed bucket stress was maintained essentially constant by careful control of engine speed. Operation was interrupted to replace fractured buckets, for necessary maintenance, and at the end of each work day. The test was completed after 407 hours of rated-speed operation. During this period, the engine was started and shut down 124 times.

Stress and Temperature Distributions in Turbine Buckets

The centrifugal stress and temperature distributions in the bucket airfoils are shown in figure 1. The centrifugal stresses along the span of the buckets were calculated by the method of reference 5, which considers bucket geometry, material density, radius of rotation, and rotational speed. Since alloy density and airfoil contour varied slightly for the different groups of buckets, a stress band, rather than a single curve, is shown in figure 1.

Spanwise bucket temperature distributions were measured by four S-816 thermocoupled buckets at the beginning of the investigation and after each major engine overhaul. After each temperature survey these buckets were removed, and only two shortened thermocoupled buckets were used to monitor bucket temperature during test operation. The curve shown in figure 1 is typical of the temperature distributions obtained. Although the airfoil temperature distributions changed after each engine overhaul, midspan bucket temperature was always maintained at 1650° F.

Expected-life curves for the buckets of each alloy are shown in figure 2. These curves depict the expected life at various positions along the airfoil if the sole cause of failure is assumed to be stress rupture. Stress-rupture data, the calculated stresses, and the temperature data obtained at rated speed (fig. 1) were used to construct these curves. Where necessary, the stress-rupture data were extrapolated using graphical and analytical methods to cover the ranges of stress and temperature involved. Figure 2 indicates that the critical zone of the airfoil, defined by minimum life, occurs in the midspan region between approximately $1\frac{3}{4}$ and $2\frac{1}{4}$ inches from the base of the airfoil.

Elongation Measurements

At convenient intervals during the test, elongation measurements of two buckets from each group were made on 1/2-inch gage lengths (scribed as shown in fig. 3) with an optical micrometer having a sensitivity of 0.0001 inch. The accuracy of these measurements was influenced by the degree of bucket oxidation, distortion, and warpage. Because of these factors, the reproducibility of the readings was limited to ±0.001 inch, or ±0.2 percent of the 1/2-inch gage lengths.

Macroscopic Examination

The test buckets were examined visually for gross cracks and damage each time the engine was shut down for routine maintenance. In addition, at each major overhaul and at convenient intervals between overhauls, all the buckets were removed from the turbine disk and inspected by fluorescent-dye penetrant methods. The location and severity of cracks and damaged areas were recorded, and the buckets were reinstalled for additional engine testing. At these inspections only buckets containing severe cracks or showing serious impact damage, which indicated that fracture was imminent, were removed from the engine.

Metallographic Examination

Metallographic studies were made of specimens cut from as-received buckets from four of the alloy groups; sufficient spare buckets from the other groups were not available for examination. The specimens were cut from the leading-edge, midchord, and trailing-edge regions at approximately midspan position. After testing, at least two buckets of each group were sectioned for examination. In most cases, the first failure and one of the later failures were examined. In the case of fracture, the metallographic specimen was taken from an area immediately adjacent to the fracture zone. In some instances, additional specimens were examined when the buckets exhibited excessive stress-rupture cracking or thermal-fatigue cracking on the leading edge.

TYPES OF BUCKET FAILURE

At the periodic inspections made during the engine test, a multiplicity of small cracks was observed on the leading edge of many buckets (fig. 4(a)). These cracks were similar to those observed in previous tests with the J47 engine (refs. 6, 7, and 8) and in one test with the J33 engine (ref. 9). It was demonstrated in the J47 engine tests (ref. 8) that this type of cracking resulted from thermal stresses induced primarily by repeated engine starts. Similar cracks observed in buckets in the present investigation apparently resulted from the same cause. It should be noted that the presence of such cracks would require removal of the buckets in normal engine service; therefore, buckets with leading-edge cracks were termed thermal-fatigue failures. During this investigation, however, buckets containing such cracks were not removed, and only buckets that had fractured or in which imminent fracture was apparent were removed. The actual fracture mechanisms are classified as follows:

(1) Stress rupture: Bucket fractures were defined either by extensive cracking across the airfoil or by parting along an irregular, jagged, intercrystalline path. Typical stress-rupture fractures are shown in figures 4(b) and (c).

(2) Mechanical fatigue: Fractures occurred by the propagation of cracks from nucleation sites, generally at or near the leading or trailing edges, in straight paths. The appearance of the fracture surface usually indicated a transcrystalline path and often showed progression lines or concentric rings (fig. 4(d)).

(3) Damage: Buckets exhibited dents or nicks from fragments of fractured buckets, or from foreign objects passing through the engine, that were so extensive as to indicate imminent fracture. Also, buckets in which fracture was seen to have propagated from a nick or dent were considered to be damage fractures.

RESULTS

Engine Testing Results

Thermal-fatigue cracking. - The buckets of all alloy groups were susceptible, in varying degrees, to leading-edge thermal-fatigue cracking. Usually these cracks were first observed by fluorescent-dye inspection methods and were less than 1/32-inch in depth on initial detection. As previously stated, buckets that cracked in this manner were not removed from the engine. With continued testing, many of these cracks propagated to greater depths; however, the degree of penetration in most cases did not exceed 1/16 inch. The uniformity of crack propagation to this depth in so many cases indicated that this was probably the extent of penetration that could be attributed to thermal stresses induced by cyclic engine operation. Penetration beyond this distance, in some cases up to 5/16 inch, was considered to have been caused by other failure mechanisms such as mechanical fatigue or stress rupture.

A graphical representation of the occurrence of thermal-fatigue cracking in buckets of each alloy group as a function of operating time at rated speed is shown in figure 5. The failure times of buckets that did not develop thermal-fatigue cracks are also shown in figure 5. These buckets were excluded from the sample if they were removed prior to the failure of a sufficient number of buckets by thermal-fatigue cracking to establish the median time to cracking for a particular group. Lot B of F-342 alloy and Inconel 713 alloy demonstrated median times to cracking of 224 and 166 hours, respectively. The other alloy groups, with the exception of vacuum-cast Udimet 500 and Guy alloy, showed median times to cracking of 100 hours or less. The latter two alloy groups had so many failures from other causes that an exact median time could not be determined. Buckets from argon-cast Udimet 500, lot A of F-342, and the NASA alloy contained thermal-fatigue cracks after 21 hours at rated speed, and some buckets of all groups contained such cracks after 154 hours. At the conclusion of the test (407 hr), thermal-fatigue cracks had been detected in 70 percent of the original test buckets. The argon-cast Udimet 500 group was considerably more susceptible to leading-edge cracking than the vacuum-cast group, since the respective median times to cracking were 21 and over 109 hours.

Median fracture life. - The times to fracture (operating lives) of the buckets of each alloy group are summarized in table III, along with a record of the location and type of each fracture. The table lists all buckets that fractured or were removed because fracture was imminent, and includes a record of damaged buckets for completeness, although damage fractures were not included in the computation of bucket life. Thermal-fatigue-cracking data are also presented in this table. As noted previously, however, buckets were not removed from the engine merely because thermal-fatigue cracking occurred.

The time to fracture and types of fracture are presented graphically in figure 6. The median lives of Inconel 713 and the NASA alloy were in excess of 407 hours, while the median lives of the remaining groups, with the exception of lot B of F-342, fell within a relatively narrow range between 90 and 160 hours. In the case of lot B of F-342 alloy, the large percentage of damage fractures made a definitive determination of median life impractical; however, it was at least 280 hours. The median life of vacuum-cast Udimet 500 was 130 hours, while that of the argon-cast group was 90 hours. In addition to longer life, appreciably less scatter was noted in the bucket-fracture data obtained with the vacuum-cast material.

In general, the buckets of most groups showed a tendency to fracture by stress rupture rather than by mechanical fatigue. Approximately two-thirds of all the fractured buckets showed evidence of a stress-rupture-type mechanism. Vacuum-cast Udimet 500 provided the major exception to this trend, since five of seven buckets fractured by mechanical fatigue. Since only one bucket from each group of lot B of F-342 and the NASA alloy fractured in a manner other than by damage, it was difficult to ascribe a significant failure trend to these alloys. In each case, however, the fracture that occurred resulted from mechanical fatigue.

Bucket elongation. - The percent elongation measured on 1/2-inch gage lengths (positions 2 and 3 in fig. 3) as a function of time at rated engine speed is plotted in figure 7 for one bucket of each alloy group. Data are shown for positions 2 and 3 only because these locations are near the critical zone of the airfoil, and, as such, displayed the greatest amount of plastic deformation. After 75 hours (the maximum time at which data were available for all groups), both the Udimet 500 and the Inconel 713 buckets showed the lowest percent elongation - less than 0.3 percent. The maximum elongation at this time (1.2 percent) occurred in the buckets of lot A of F-342. The highest recorded elongation (2.2 percent) was observed in the NASA alloy buckets at 407 hours. None of the elongation values observed appears to be excessive. In general, the elongation data are comparable to those obtained with other nickel-base alloys in previous investigations (refs. 2, 3, and 9). No significant difference was observed between the elongations of vacuum-cast and argon-cast Udimet 500 buckets.

Metallographic Examination

As-received buckets. - Photomicrographs of as-received buckets from argon-cast Udimet 500, argon-cast Guy alloy, the NASA alloy, and Inconel 713 are shown in figure 8. As indicated previously, metallographic examinations were not made of as-received buckets of the remaining four alloy groups because of the limited number of buckets available. The microstructures of the as-received buckets are typical of high-temperature nickel-base alloys; all contain fine precipitates of minor phases distributed throughout the grain structure.

Engine tested buckets. - Typical microstructures of engine tested buckets are shown in figure 9. Comparison of the as-received and engine tested buckets of argon-cast Udimet 500, argon-cast Guy alloy, the NASA alloy, and Inconel 713 (figs. 8(a) to (d) and 9(a) to (d)) indicates no marked change in microstructure.

Photomicrographs of leading-edge thermal-fatigue cracks, such as those that occurred in the majority of buckets tested, are shown in figure 10. Most of the cracks observed in buckets of all alloy groups propagated along intercrystalline paths (fig. 10(a)), but, in a few cases, transgranular cracks were noted (fig. 10(b)).

In the case of the NASA alloy, thermal-fatigue cracks appeared to have originated in a heavy scale that formed on the bucket leading edge. Figure 11 is a photomicrograph of the leading-edge region of an NASA alloy bucket showing such a crack. A photomicrograph of the cross section of an NASA alloy bucket at the leading edge after 224 hours of testing is shown in figure 12. As indicated in the figure, the scale was very thick at the leading edge (up to 0.025 in.) but its thickness decreased markedly back from the leading edge. After 407 hours of testing, the scale formation at the leading edge was approximately 0.060 inch. On all surfaces of the buckets other than the immediate leading-edge region, the thickness of the scale was on the order of 0.001 to 0.002 inch. This type of intensive localized scaling was not observed on buckets of the other materials. Although some scaling occurred, it was, in all cases, a thin uniform film not exceeding 0.002 inch in thickness.

DISCUSSION

Factors Affecting Bucket Life

The fact that 70 percent of the buckets developed thermal-fatigue cracks during the engine test indicates that thermal fatigue is an important factor to be considered in the application of these alloys as turbine-bucket materials. Since the occurrence of such cracks in normal engine service requires removal of the buckets, their useful life is influenced greatly by susceptibility to thermal fatigue. It should be noted, however, that, since such thermal-fatigue cracks are caused primarily by thermal stresses that occur during transient engine operations, the severity of this problem in a specific application will depend on the operating characteristics of the particular engine. In a previous investigation with a J47 engine (ref. 8) the magnitude of these transient thermal stresses was reduced considerably by prescribing a less severe engine starting procedure. Similar starting and acceleration procedures may be employed in other engines by designing the fuel control system to permit a greater flexibility in transient engine operating characteristics. Thus, by mitigating the severity of the thermal-stress problem, it should be possible to reduce the incidence of thermal-fatigue cracking observed in buckets of the alloys investigated herein.

Most of the alloy groups considered in this investigation exhibited median fracture lives appreciably below the expected lives based on stress-rupture properties. As shown in figure 6, five of the eight alloy groups had median lives below 160 hours, while the expected lives ranged from 400 to over 1000 hours (fig. 2). A number of factors can contribute to reductions of this type, some of which stem solely from the engine operating environment. These factors include cyclic thermal stresses, vibratory stresses, and the corrosive action of the combustion gases; other factors are the result of fabrication variables.

The direct result of thermal stresses induced by cyclic engine operation was evidenced by the previously described thermal-fatigue cracking that occurred on the bucket leading edges. As indicated in figure 5, seven of the eight alloy groups developed leading-edge cracks in less than 100 hours. Although thermal-fatigue cracks alone would not be expected to cause immediate bucket failure, their occurrence early in the test would be expected to influence bucket life. It may be noted from table III that, of the buckets that fractured after the occurrence of leading-edge thermal-fatigue cracks, 60 percent of the fractures originated at the leading edge. There are several ways in which thermal-fatigue cracks could have reduced bucket life: For example, the occurrence of thermal-fatigue cracks in the critical zone of the airfoil may have accelerated the stress-rupture-type failures by creating stress concentrations in this region. In addition, some of these small cracks may have acted as nucleation sites for mechanical-fatigue cracks. Finally, these small cracks probably increased the susceptibility of the buckets to intergranular corrosion by exposing a greater portion of the grain structure.

The effect of vibration on the buckets was evidenced by mechanical fatigue, which occurred in about one-third of the buckets that fractured. Crack propagation in these instances was transgranular, and the familiar progression lines or concentric rings associated with mechanical fatigue were apparent on many of the fracture surfaces. It is probable that mechanical-fatigue damage also shortened the life of buckets that appeared to fail by a stress-rupture-type fracture. This form of fatigue damage was demonstrated in the investigation of reference 10 in which stress-rupture specimens were subjected to superimposed vibratory loads. It was found that for "A" factors (ratio of alternating stress to mean stress) below certain values no visible evidence of mechanical fatigue was apparent on the fracture surface even though the stress-rupture life (based on mean stress) had been substantially reduced.

In addition to the preceding variables resulting from engine testing, defects such as porosity and dross inclusions introduced during fabrication could also result in premature bucket failure. Although most defects of this type are detectable, their occurrence on a microscale can render them undetectable by conventional inspection techniques. These defects could act as nucleation sites or stress concentrations from which premature bucket failure might be initiated through a variety of mechanisms.

Significance of Engine Testing Results

Although median fracture lives of most alloy groups were well below the expected lives, as predicted from stress-rupture properties, the buckets of all groups were operated for reasonably long times. As depicted in figure 6, the lowest median fracture life was about 90 hours, while two alloy groups had median lives in excess of 407 hours. The bucket lives, of all alloys tested, obtained in the J33 engine at a midspan bucket temperature of 1650° F, compare favorably with the performance of more conventionally used bucket alloys operated in the same engine at 1500° F. A typical example of bucket performance under the latter circumstances is given in the investigation of reference 11, in which a control group of 17 standard S-816 buckets (Air Force stock) failed in times ranging from 50 to 340 hours and demonstrated a median life of 151 hours.

In addition to the relatively favorable bucket lives obtained with the alloys of this investigation, most of the materials demonstrated the ability to operate for extended periods of time after thermal-fatigue cracks had developed along the leading edge. Buckets of the NASA alloy and Inconel 713 were operated for as long as 386 and 298 hours, respectively, after such cracks had been detected. Also, with the exception of vacuum-cast Guy alloy, at least one bucket of each alloy group was operated more than 100 hours with such cracks on the leading edge. Furthermore, buckets containing thermal-fatigue cracks on the leading edge did not necessarily fracture by propagation of these cracks. As indicated in table III, the origin of fracture of many buckets containing thermal-fatigue cracks occurred at the midchord or at the trailing edge. These results indicate that the cast nickel-base alloys considered in this investigation were, in general, relatively insensitive to the presence of these cracks.

As previously mentioned (fig. 12), a rather heavy scale formed on the leading edge of the NASA alloy buckets. Despite the presence of this scale, these buckets demonstrated good performance from the standpoint of operating life. Although the scaling was noted early in the test (less than 100 hr), only one of the NASA buckets had fractured when the test was terminated after 407 hours.

This investigation gave no evidence that any of the bucket materials was particularly sensitive to impact damage. During engine testing, many fragments of fractured buckets impacted other buckets in the turbine, but in no case did these fragments cause immediate bucket fracture as a result of such impact. Occasionally, small chips were broken from the tip section of the impacted buckets, but, in general, buckets of all alloy groups demonstrated good impact resistance.

It is evident from the engine testing results that the cast nickel-base alloys considered herein demonstrated a substantial capability as turbine-bucket materials. Although certain alloy groups performed more favorably than others, it appears that any of these alloys may be employed as turbine-bucket materials at temperatures considerably above current levels.

SUMMARY OF RESULTS

An investigation was conducted to determine the times to failure and failure mechanisms of buckets of various nickel-base alloys in a modified J33 engine. The engine was operated with a midspan bucket temperature of 1650° F (turbine-inlet temperature, 1800° F). The alloys investigated included Inconel 713, Udimet 500, Guy alloy, F-342, and an early experimental NASA alloy. The following major results were obtained:

1. Seventy percent of the buckets developed thermal-fatigue cracks on the leading edge during the engine test. Cracks were observed on buckets of some alloy groups after 21 hours and in all groups after 154 hours. The median time to cracking in the various groups ranged from 21 to 224 hours.

2. The median bucket fracture life at rated-speed conditions ranged from approximately 90 to more than 407 hours. The bucket lives, obtained in the J33 engine at a midspan bucket temperature of 1650° F, are comparable to the performance of more conventionally used bucket alloys in the same engine at 1500° F. The shortest median fracture life was obtained with argon-cast Udimet 500. Buckets of Inconel 713 and the NASA alloy had median lives greater than 407 hours, the time at which the test was terminated. For each case in which median fracture life could be determined, it was well below the expected bucket life based on material stress-rupture properties.

3. Two-thirds of the bucket fractures were of the stress-rupture type, while the remainder contained visible evidence of mechanical fatigue.

4. The bucket elongations observed were not excessive, the maximum being on the order of 2 percent after 407 hours.

5. The buckets of all alloy groups exhibited good impact resistance when struck by fragments of fractured buckets, since no immediate fracture resulted from such an impact.

6. The performance of the vacuum-cast Udimet 500 buckets was better than that of the argon-cast group on the basis of median fracture life (130 compared with 90 hr), as well as the median time to thermal-fatigue cracking (over 109 to 21 hr).

7. Although a heavy scale formed on the leading edge of the NASA alloy buckets early in the test, these buckets demonstrated good performance on the basis of engine-operating life.

Lewis Research Center
National Aeronautics and Space Administration
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TABLE I. - TYPICAL CHEMICAL COMPOSITION OF BUCKET MATERIALS

Alloy	Composition, percent by weight												
	Ni	Co	Cr	Mo	Cb	Ti	Al	Zr	B	C	Si	Fe	Mn
Udimet 500	Bal.	17	19	4	-	3	3	-	---	0.1	----	2	----
Guy		--	13.5	5.5	2	---	6.25	-	0.5	.1	0.5	4.5	0.5
F-342		--	15	5	-	---	5	-	.3	.14	.40	5	.40
NASA		--	6	8	-	1.5	6	1	---	.125	----	---	----
Inconel 713		--	12	4.5	2	.5	6	-	---	.12	.40	---	.15

TABLE II. - CASTING PROCEDURES AND SOURCES OF BUCKET MATERIALS

Alloy group	Number of buckets	Casting procedure		Source
Argon-cast Udimet 500	7	Vacuum-melted master heat	Remelted and cast under argon cover	Austenal Co.
Vacuum-cast Udimet 500	7		Remelted and cast in vacuum	
Vacuum-cast Guy	7	Melted and cast in vacuum		
Argon-cast Guy	6	Melted and cast under argon cover		
F-342 (lot A)	6			Allegheny Ludlum Steel Corp.
F-342 (lot B)	6			Austenal Co.
NASA	6	Melted under argon cover, cast in air		NASA Lewis Research Center
Inconel 713	7	Melted and cast in vacuum		Austenal Co.

TABLE III. - TIME TO FRACTURE, TYPES OF FRACTURE, AND ORIGIN OF FRACTURE OBSERVED DURING ENGINE EVALUATION OF BUCKET MATERIALS

Alloy group	Time to first crack,[a] hr	Time to fracture, hr	Type of fracture (b)	Origin of fracture	
				Distance above base, in.	Chordwise position
Argon-cast Udimet 500	21.0	21.0	S-R	1.9	Leading edge
	21.0	90.8	S-R	1.1-2.4	
	21.0	90.8	S-R	0.8-2.6	
	21.0	97.4	F	1.2	
	62.0	166.0	D	-------	-------------
	----	278.0	F	2.7	Trailing edge
	21.0	327.8	D	-------	-------------
Vacuum-cast Udimet 500	----	109.3	F	2.3	Trailing edge
	----	113.5	F	2.2	
	40.0	119.8	F	2.5	
	62.0	131.0	S-R	1.9	Leading edge
	----	132.0	S-R	3.0	Trailing edge
	----	154.0	F	2.8	Trailing edge
	40.0	205.0	F	1.2	Leading edge
Vacuum-cast Guy	-----	40.0	S-R	1.0-1.9	Midchord
	90.8	104.3	S-R	1.7	Midchord
	-----	109.3	S-R	1.2-1.8	Leading edge
	109.3	119.8	D	-------	------------
	-----	154.0	S-R	1.1-2.0	Midchord
	90.8	166.0	S-R	0.8-1.1	Midchord
	-----	166.0	D	-------	------------
Argon-cast Guy	90.8	109.3	D	-------	------------
	62.0	109.3	S-R	1.1-2.9	Leading edge
	-----	109.3	D	-------	------------
	109.3	154.0	D	-------	------------
	-----	154.0	S-R	1.3-1.8	Midchord
	90.8	224.0	S-R	1.8-2.8	Midchord

Alloy group	Time to first crack,[a] hr	Time to fracture, hr	Type of fracture (b)	Origin of fracture	
				Distance above base, in.	Chordwise position
F-342 (lot A)	90.8	104.3	S-R	1.5-1.7	Midchord
	40.0	104.3	F	1.9	Leading edge
	90.8	104.3	S-R	2.3	Midchord
	62.0	166.0	S-R	1.7-2.0	Midchord
	21.0	175.0	F	2.6	Leading edge
	109.3	224.0	S-R	1.6-2.2	Midchord
F-342 (lot B)	-----	166.0	D	-------	------------
	-----	206.5	D	-------	------------
	-----	280.5	D	-------	------------
	154.0	280.5	F	0.8	Leading edge
	224.0	407.0	None	-------	------------
	224.0	407.0	None	-------	------------
NASA	90.8	224.0	None[c]	-------	------------
	260.0	340.5	F	1.4	Leading edge
	90.8	407.0	None	-------	------------
	90.8			-------	------------
	21.0			-------	------------
	-----			-------	------------
Inconel 713	-----	189.5	S-R	1.8	Leading edge
	62.0	224.0	S-R	1.9	Leading edge
	224.0	407.0	None	-------	------------
	109.3	407.0		-------	------------
	109.3			-------	------------
	224.0			-------	------------
	327.0			-------	------------

[a]Thermal-fatigue cracks on bucket leading edge.
[b]S-R, stress-rupture fracture or cracking; F, mechanical fatigue; D, damage.
[c]Bucket removed for metallographic examination.

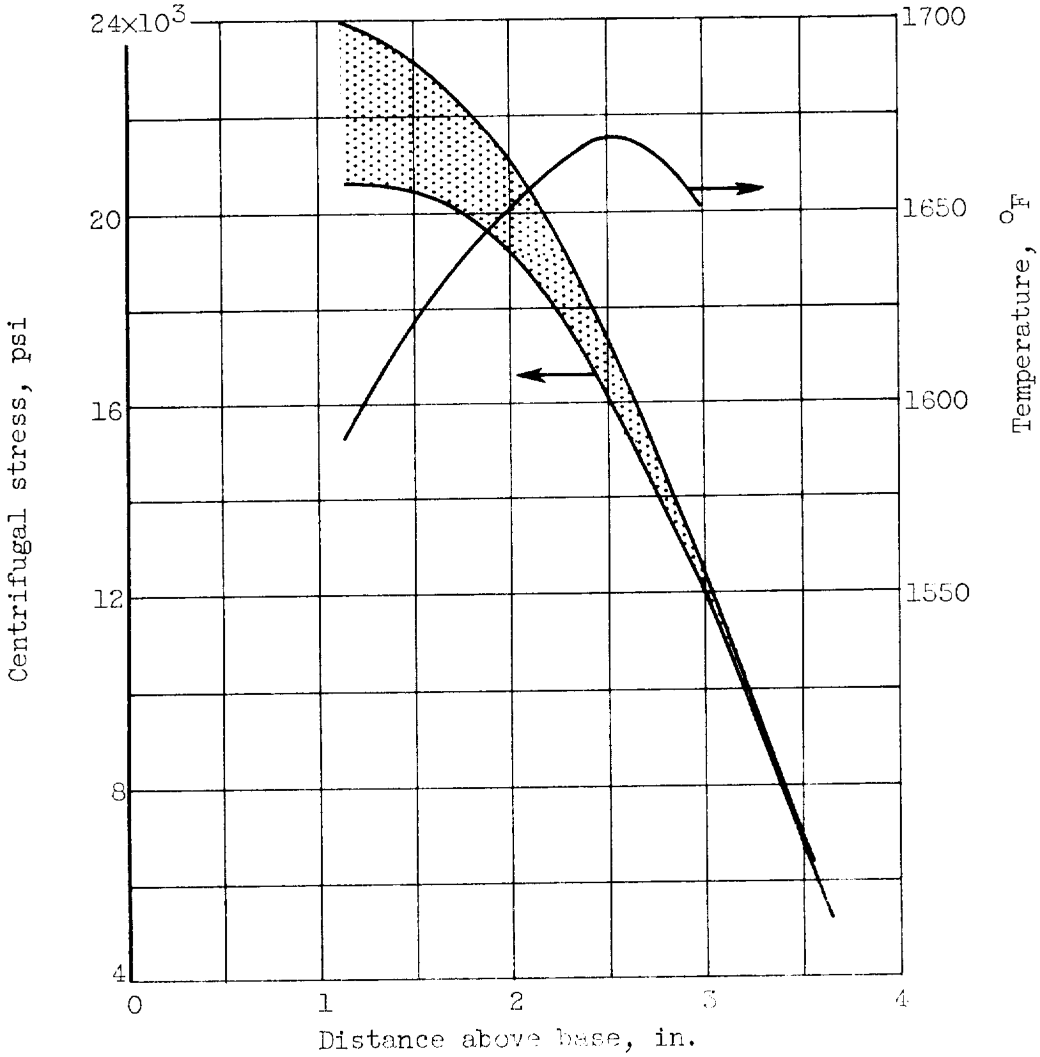


Figure 1. - Centrifugal stress and temperature distributions in turbine-bucket airfoils at rated-speed conditions.

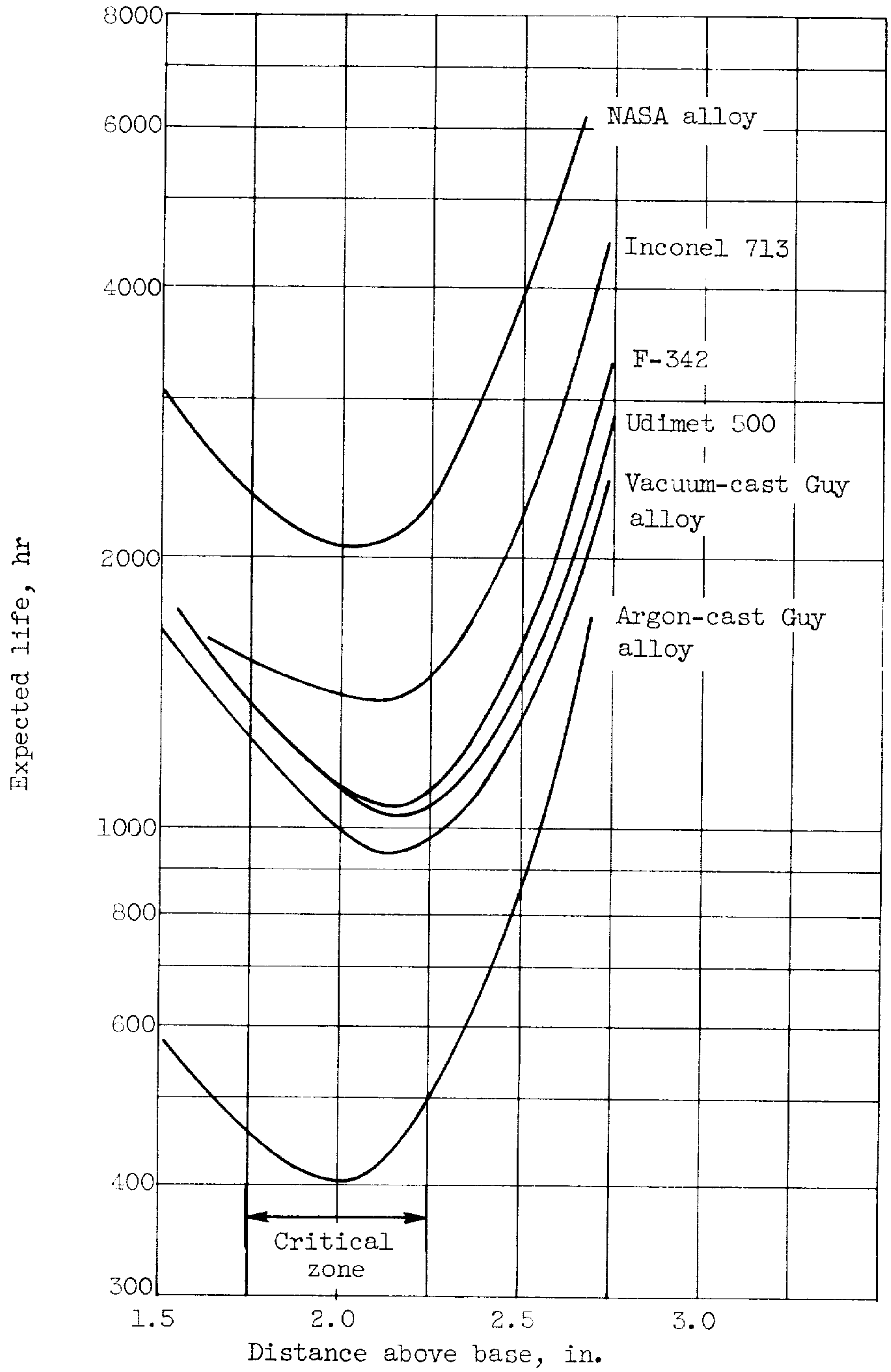


Figure 2. - Expected-life curves for bucket materials in J33-9 engine at rated speed with midspan bucket temperature of 1650° F.

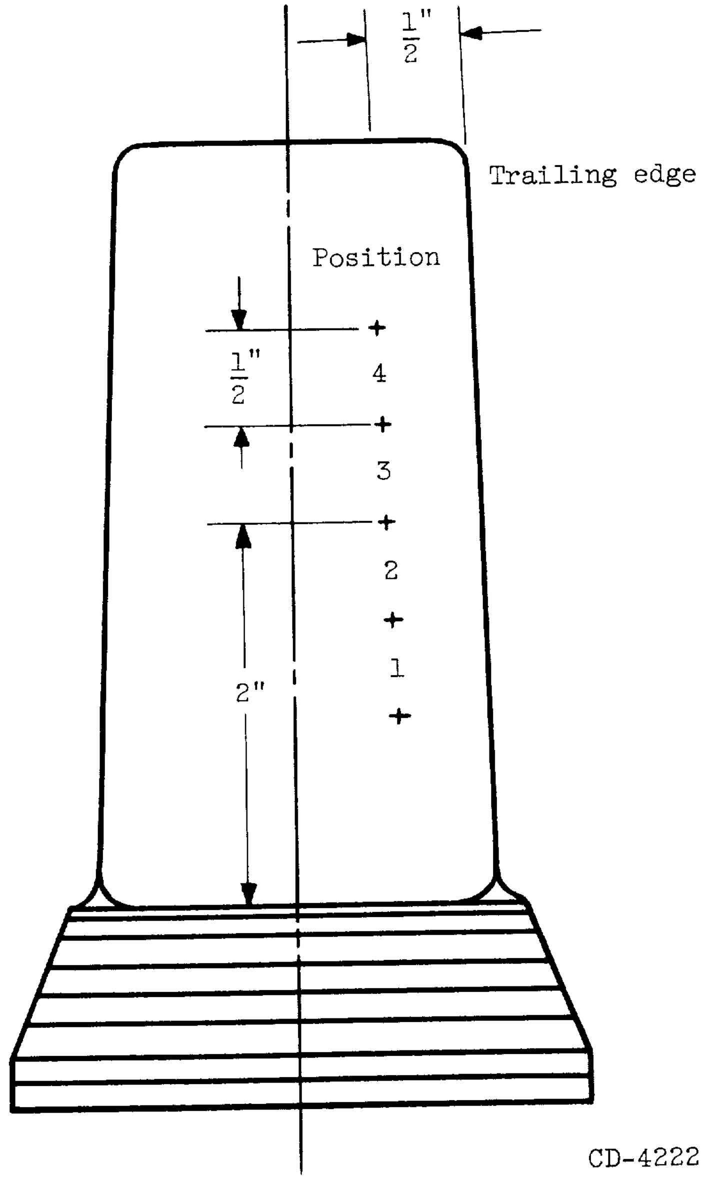
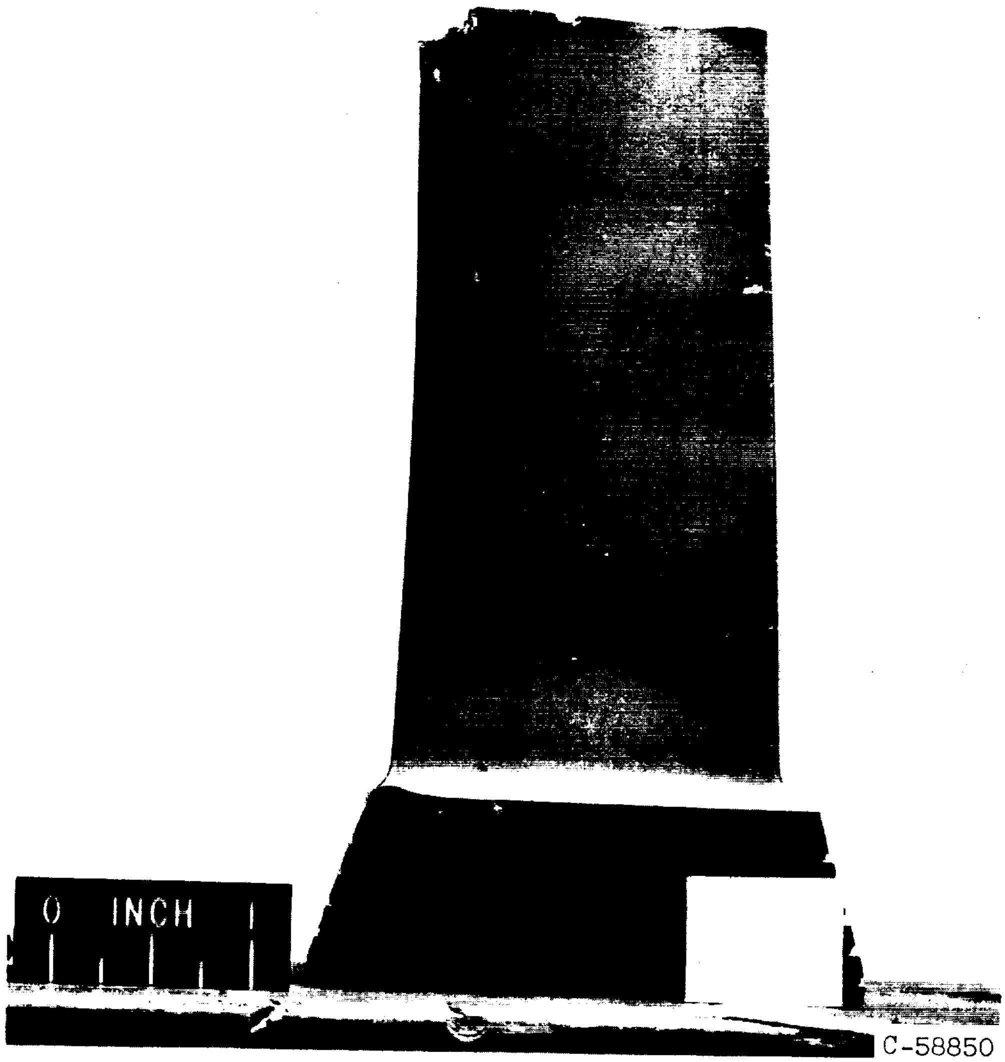


Figure 3. - Location of elongation gage marks on bucket airfoil.



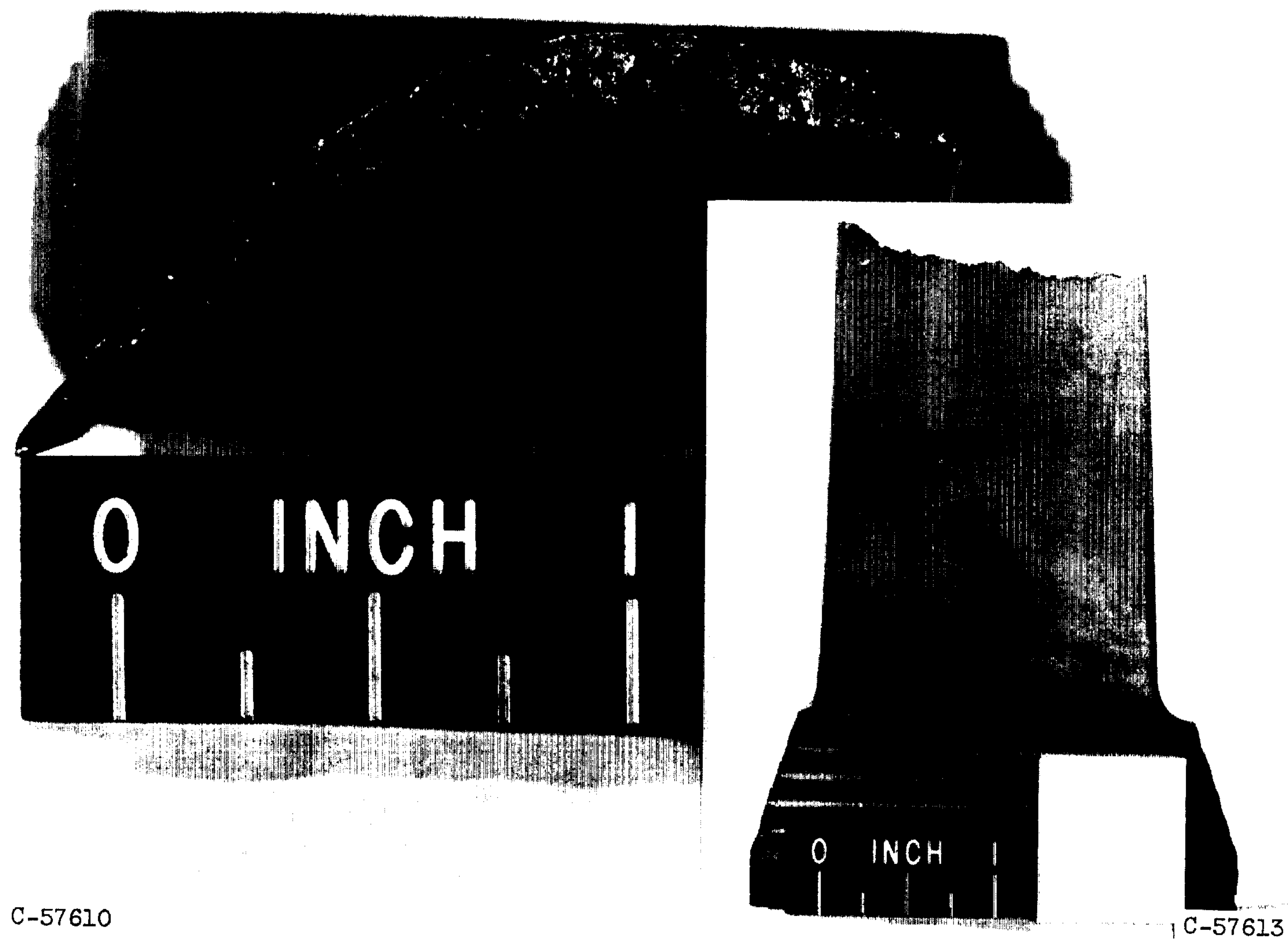
(a) Thermal-fatigue cracking.

Figure 4. - Types of bucket failures resulting from engine testing.

C-57615

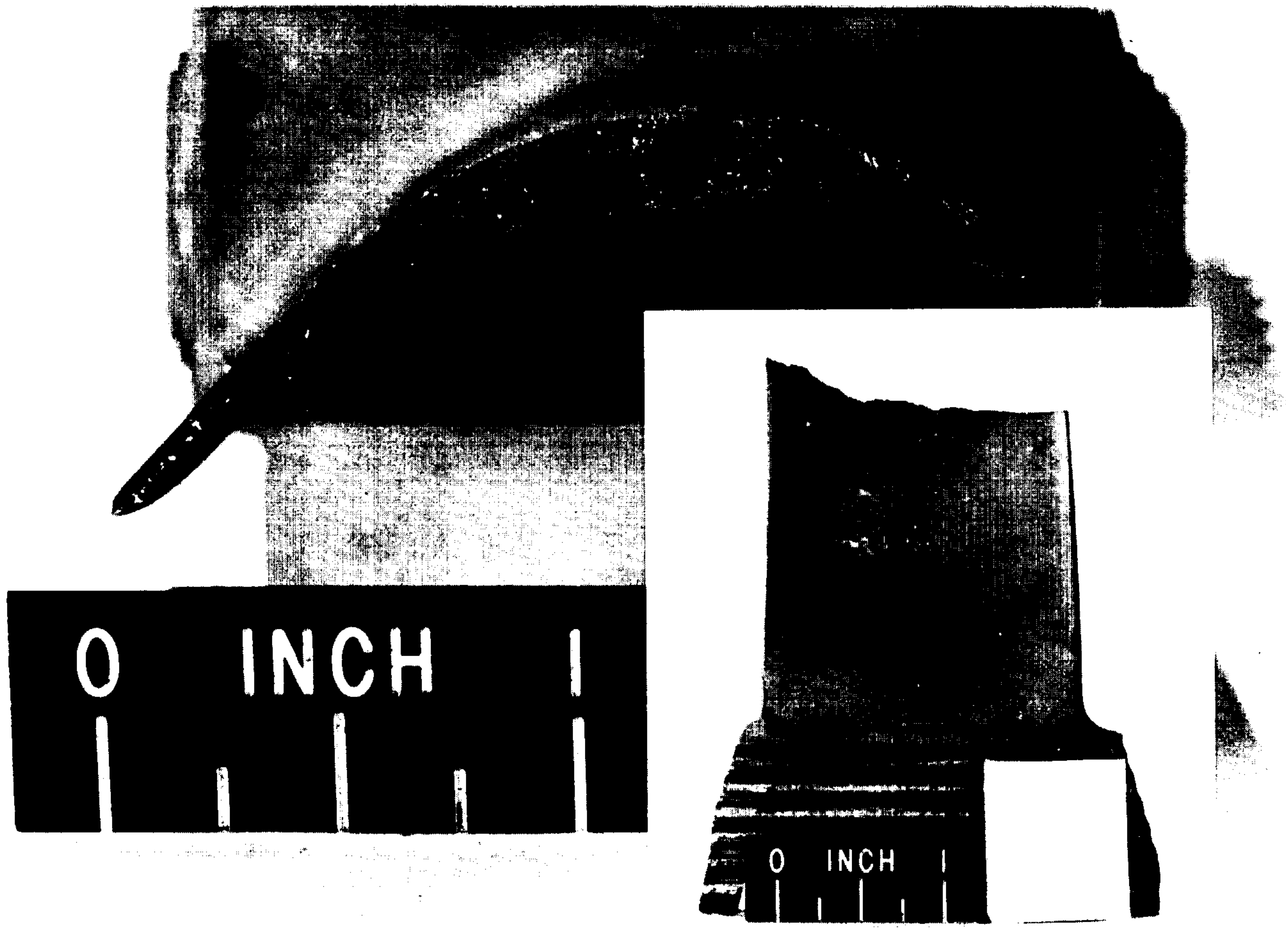
(b) Stress-rupture cracking.

Figure 4. - Continued. Types of bucket failures resulting from engine testing.



(c) Stress-rupture fracture.

Figure 4. - Continued. Types of bucket failures resulting from engine testing.



C-57611

C-57612

(d) Mechanical-fatigue fracture.

Figure 4. - Concluded. Types of bucket failures resulting from engine testing.

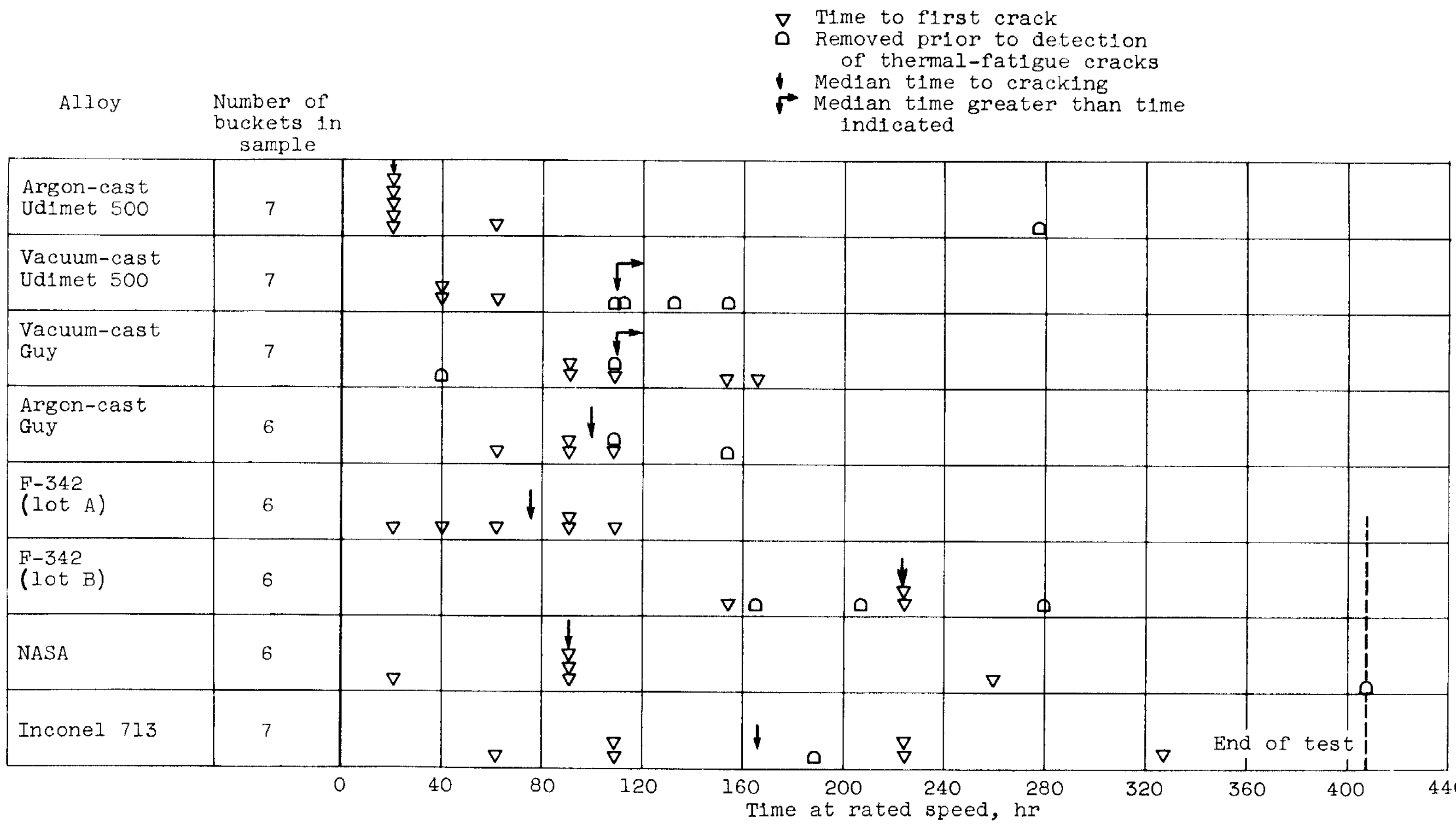


Figure 5. - Incidence of thermal-fatigue cracking in turbine buckets.

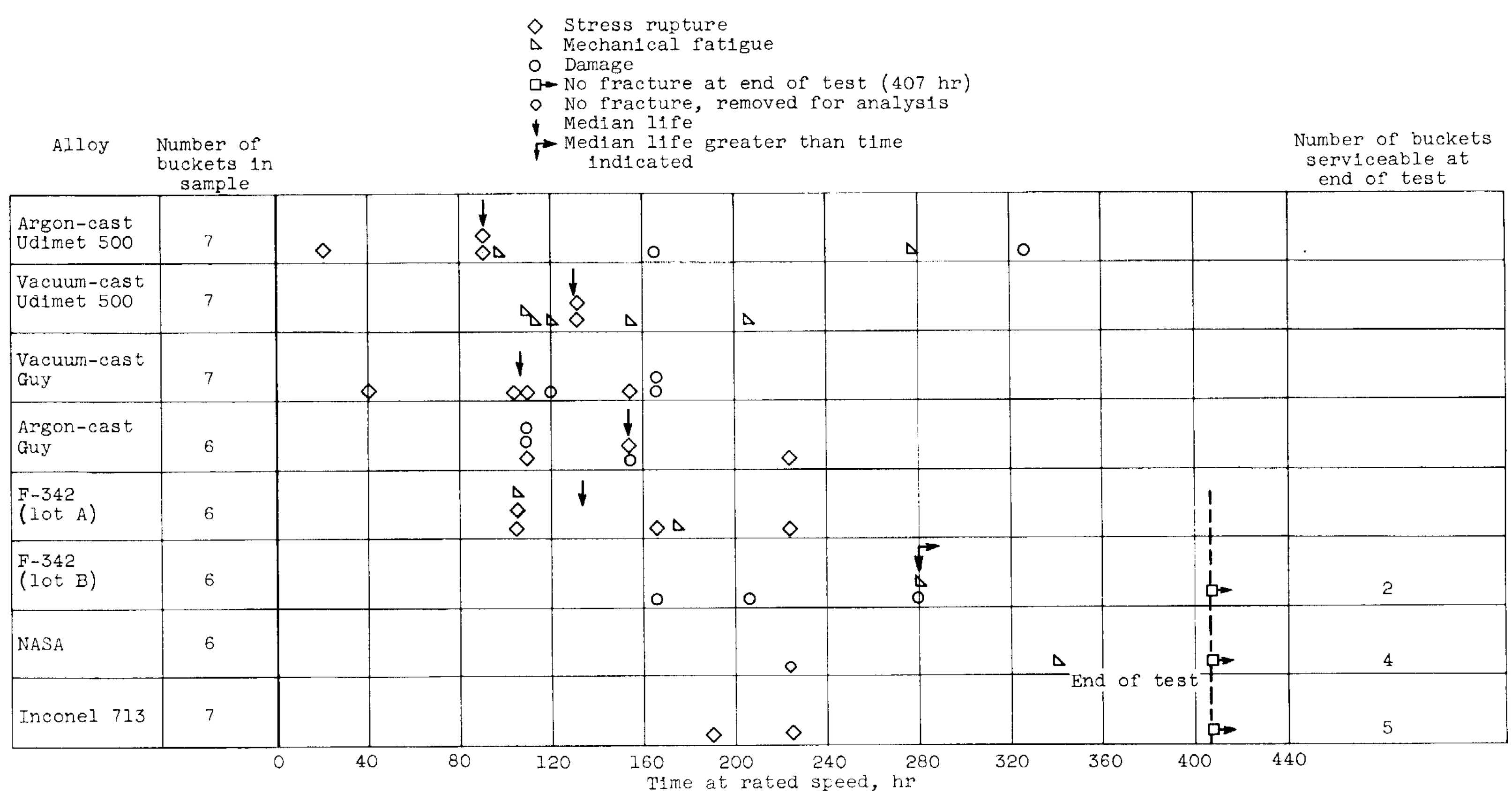
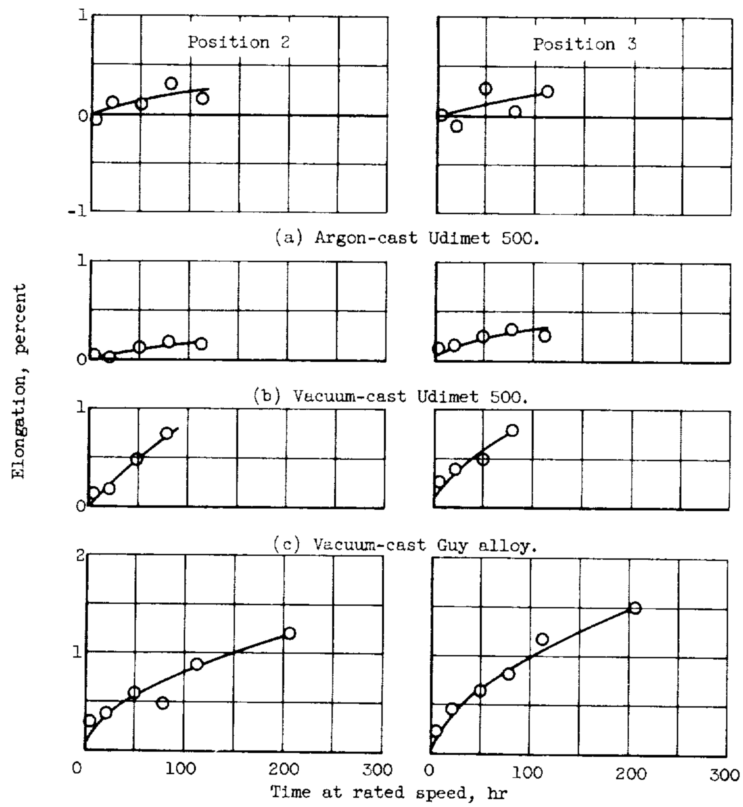
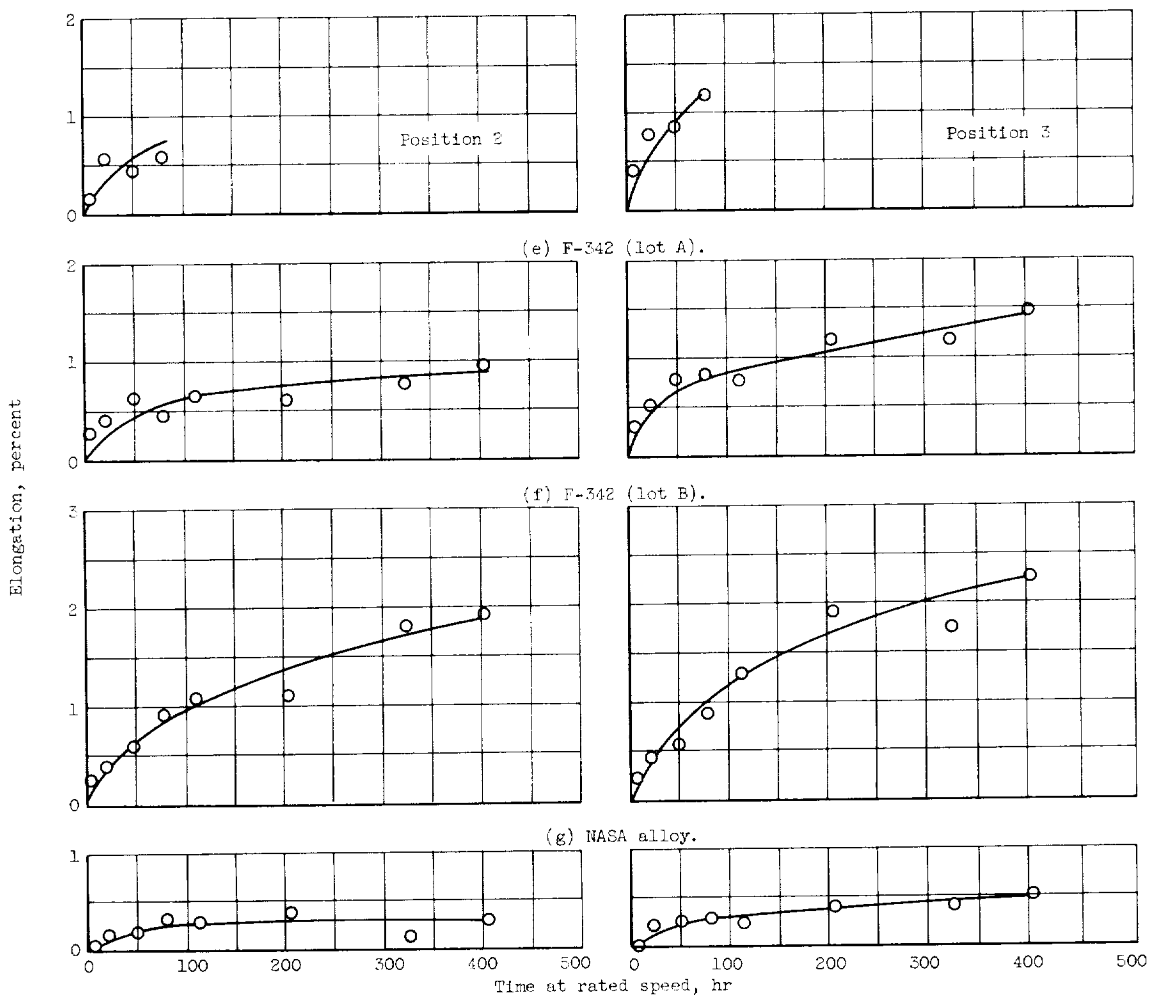


Figure 6. - Operating life of bucket materials at rated-speed conditions.



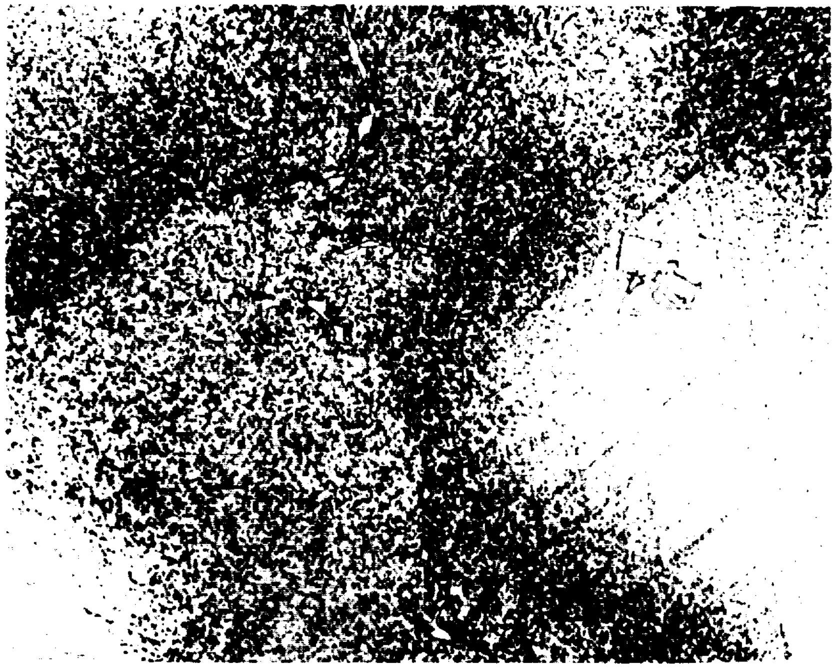
(d) Argon-cast Guy alloy.

Figure 7. - Elongation of bucket materials in J33-9 engine operating at 11,500 rpm. Midspan bucket temperature, 1650° F.



(h) Inconel 713.

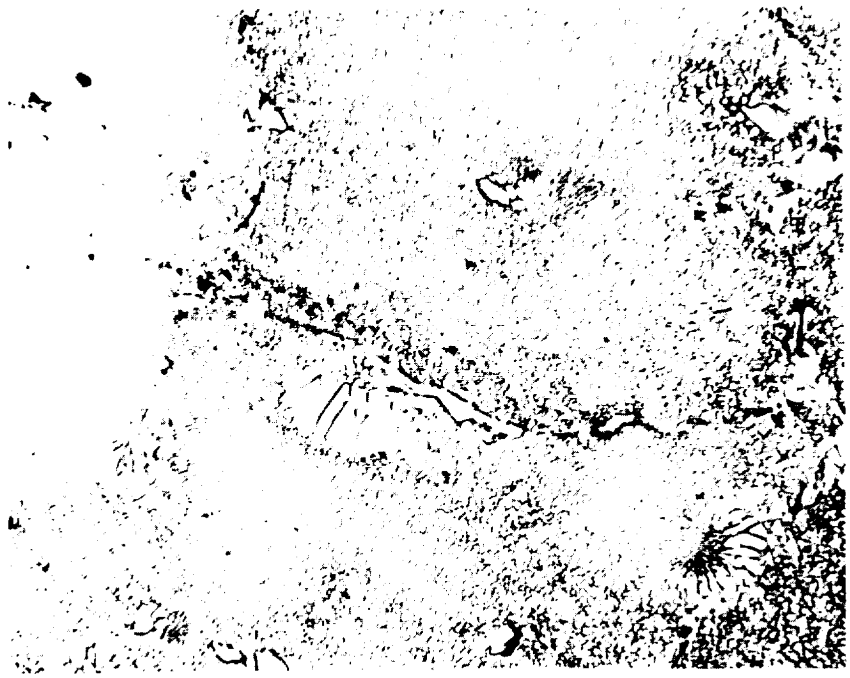
Figure 7. - Concluded. Elongation of bucket materials in J33 engine operating at 11,500 rpm. Midspan bucket temperature, 1650° F.



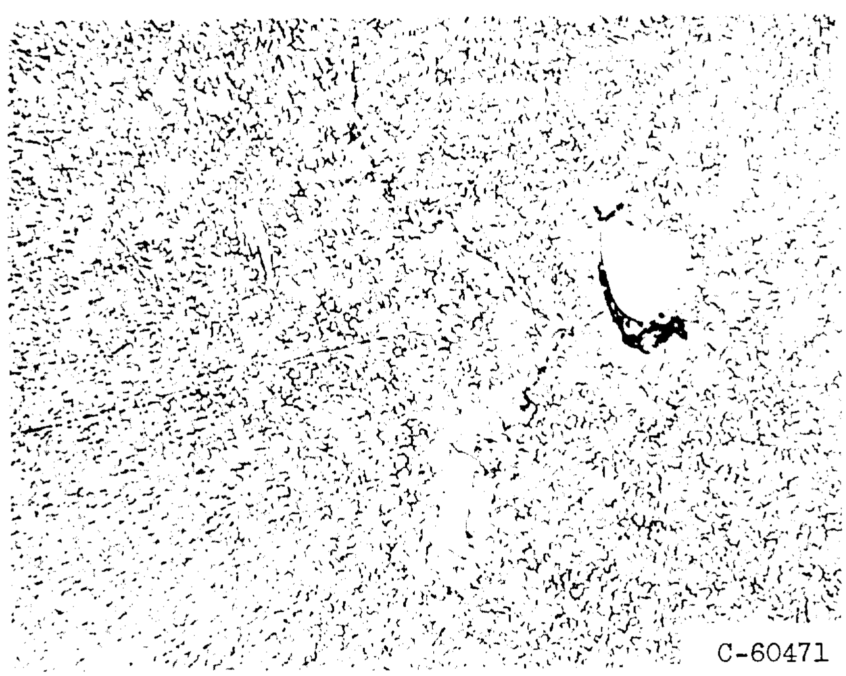
(a) Argon-cast Udimet 500.

(b) Argon-cast Guy alloy.

Figure 8. - Typical microstructures of as-received buckets. Etchant: 20 parts glycerine, 20 parts H_2O, 10 parts HNO_3, 5 parts HF. ×750.

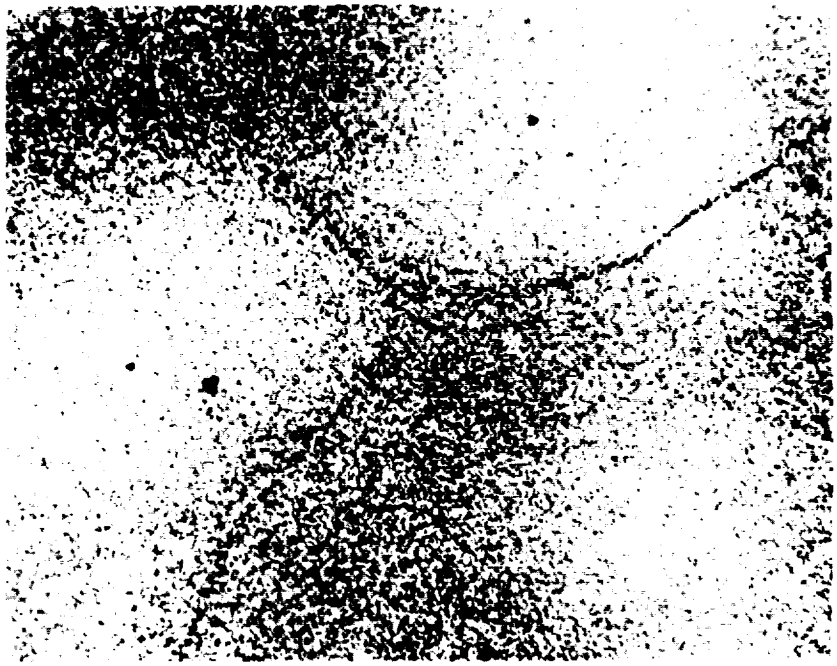


(c) NASA alloy.



(d) Inconel 713.

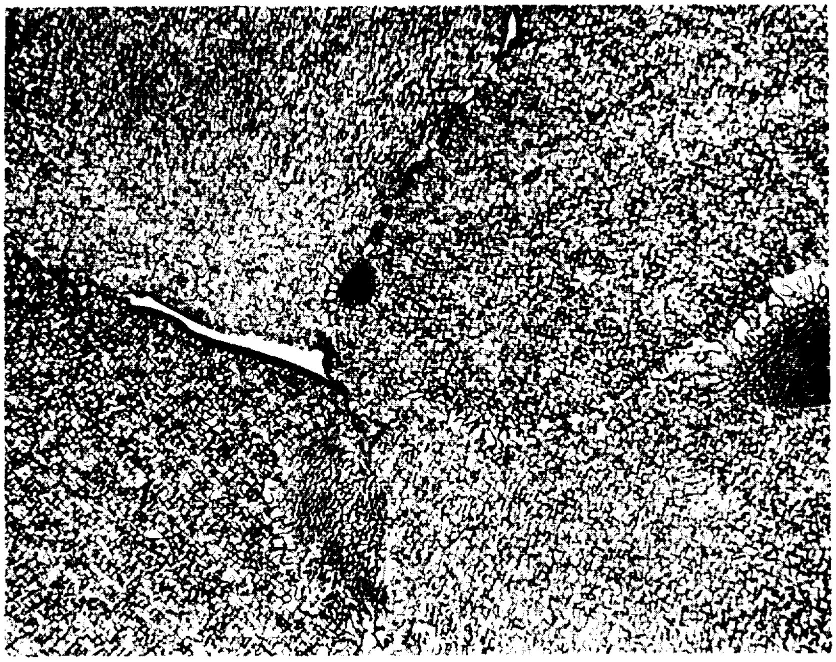
Figure 8. - Concluded. Typical microstructures of as-received buckets. Etchant: 20 parts glycerine, 20 parts H_2O, 10 parts HNO_3, 5 parts HF. ×750.



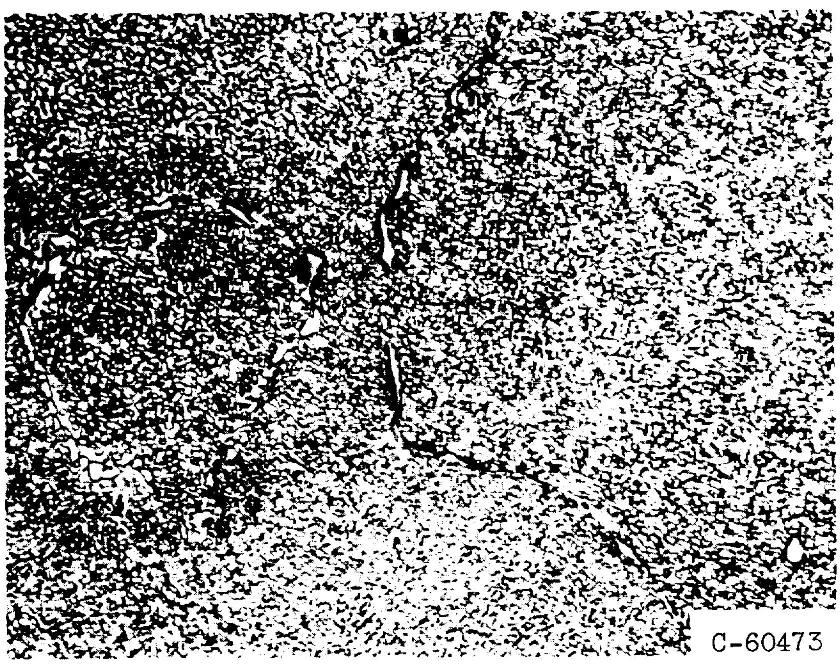
(a) Argon-cast Udimet 500.

(b) Argon-cast Guy alloy.

Figure 9. - Typical microstructures of engine-tested buckets. Etchant: 20 parts glycerine, 20 parts H_2O, 10 parts HNO_3, 5 parts HF. ×750.

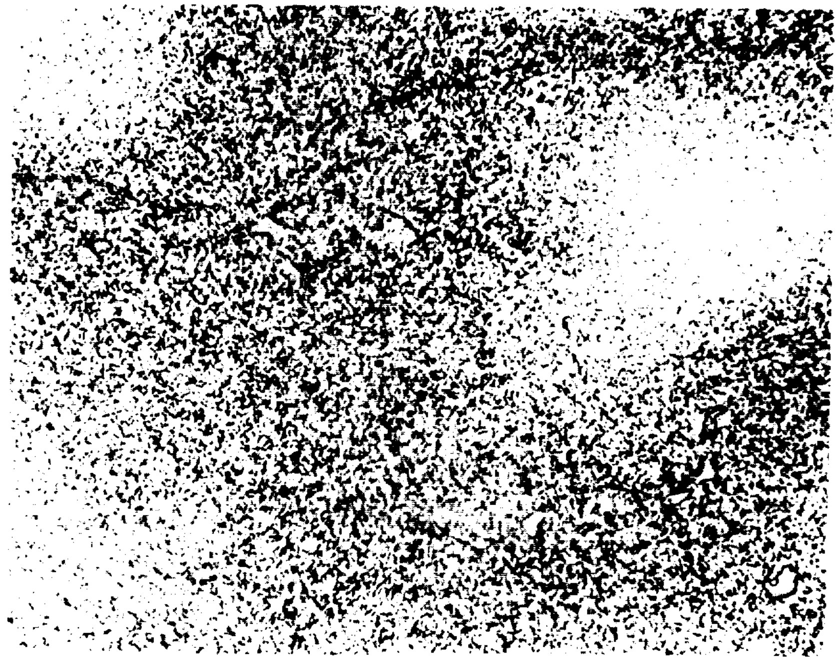


(c) NASA alloy.

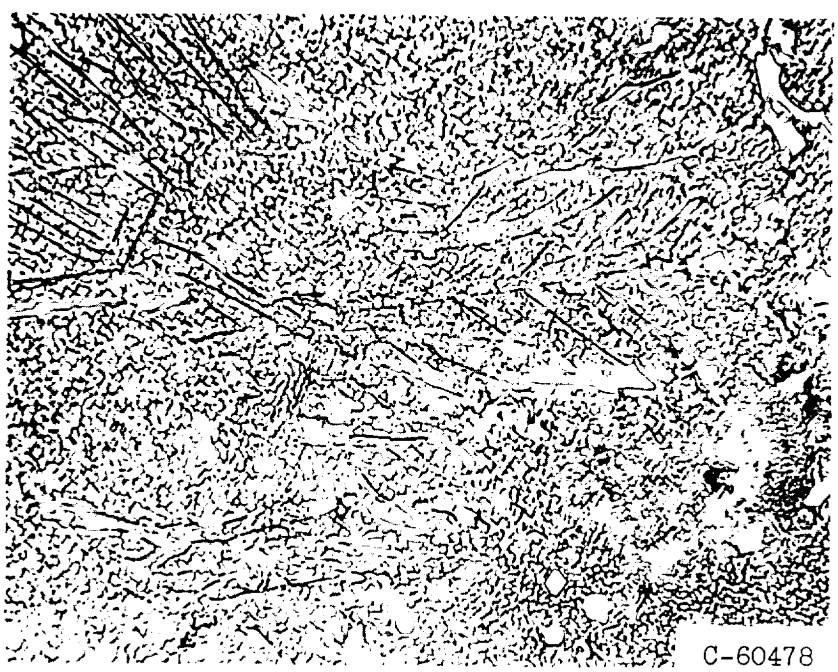


(d) Inconel 713.

Figure 9. - Continued. Typical microstructures of engine-tested buckets. Etchant: 20 parts glycerine, 20 parts H_2O, 10 parts HNO_3, 5 parts HF. ×750.

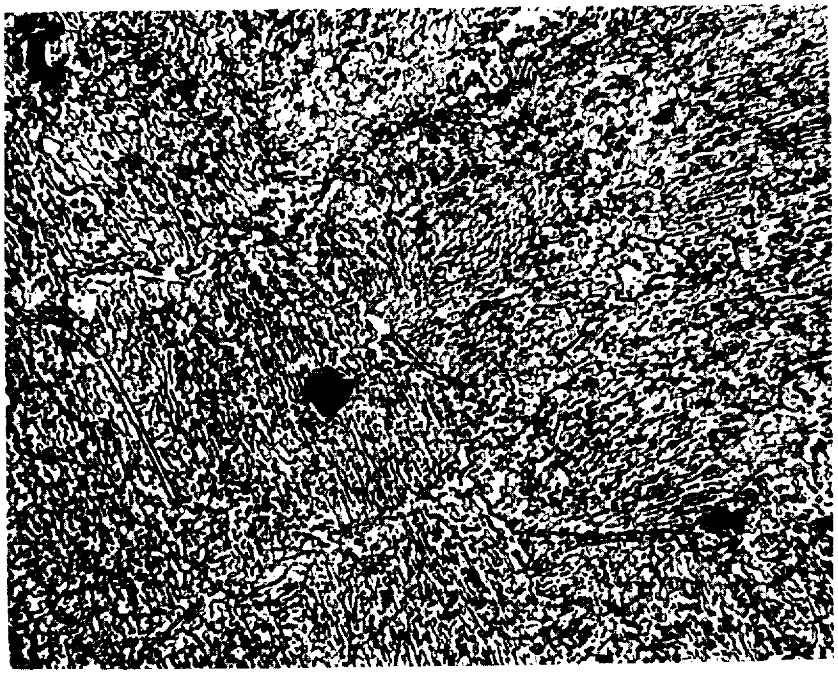


(e) Vacuum-cast Udimet 500.

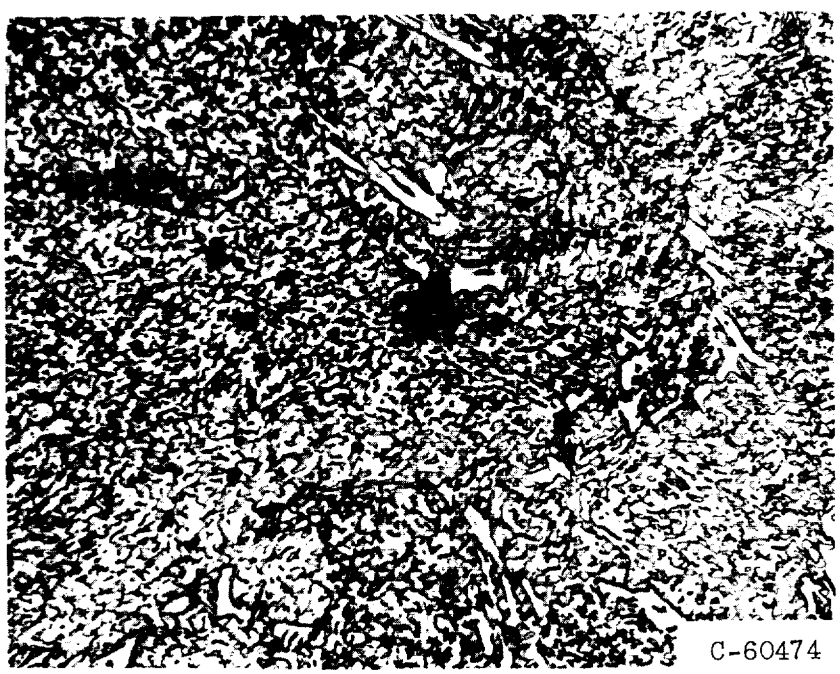


(f) Vacuum-cast Guy alloy.

Figure 9. - Continued. Typical microstructures of engine-tested buckets. Etchant: 20 parts glycerine, 20 parts H_2O, 10 parts HNO_3, 5 parts HF. ×750.

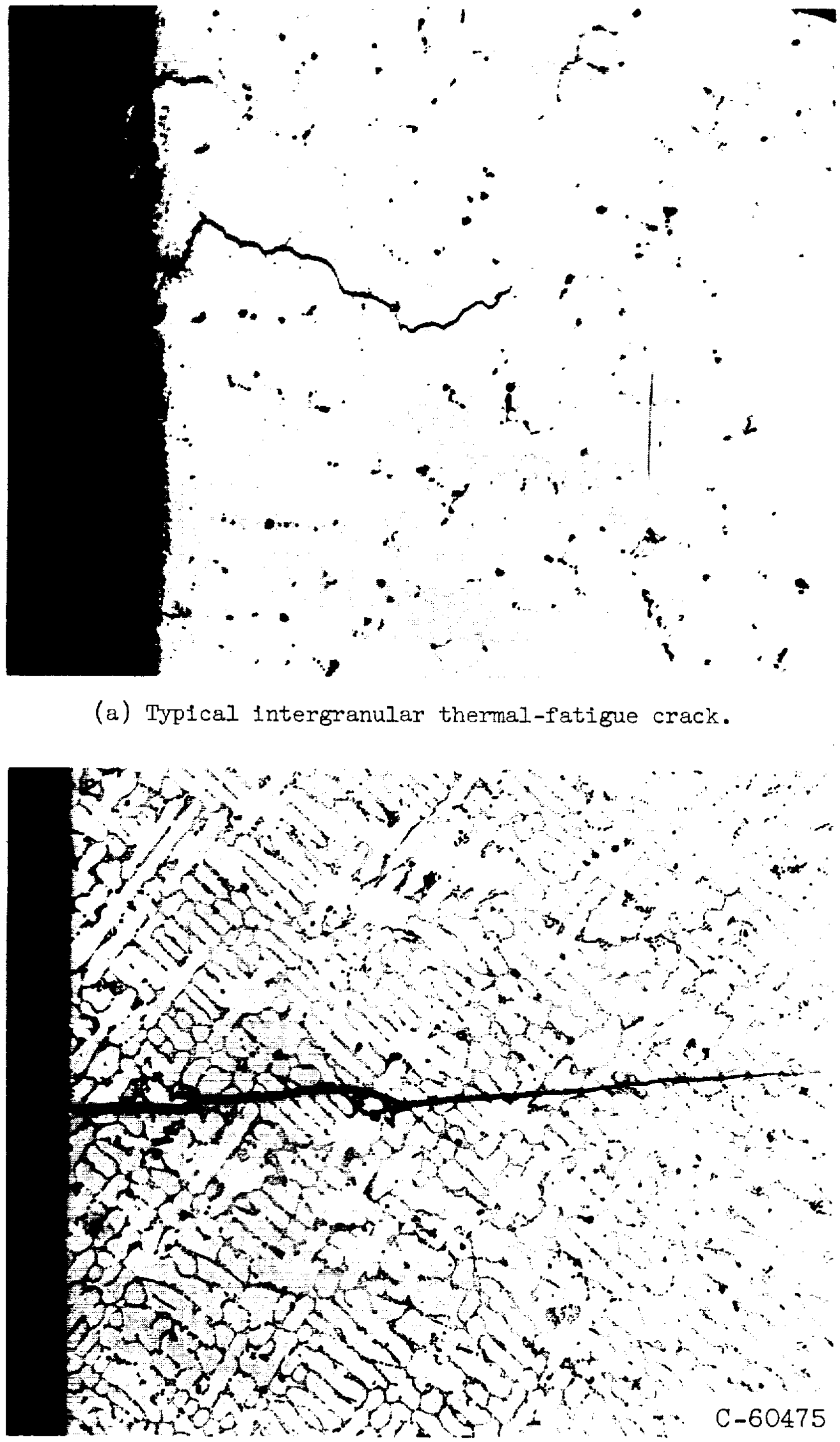


(g) F-342, lot A.



(h) F-342, lot B.

Figure 9. - Concluded. Typical microstructures of engine-tested buckets. Etchant: 20 parts glycerine, 20 parts H_2O, 10 parts HNO_3, 5 parts HF. ×750.



(a) Typical intergranular thermal-fatigue crack.

(b) Typical transgranular thermal-fatigue crack.

Figure 10. - Types of thermal-fatigue cracks observed on leading edges of engine-tested buckets. Unetched. ×100.

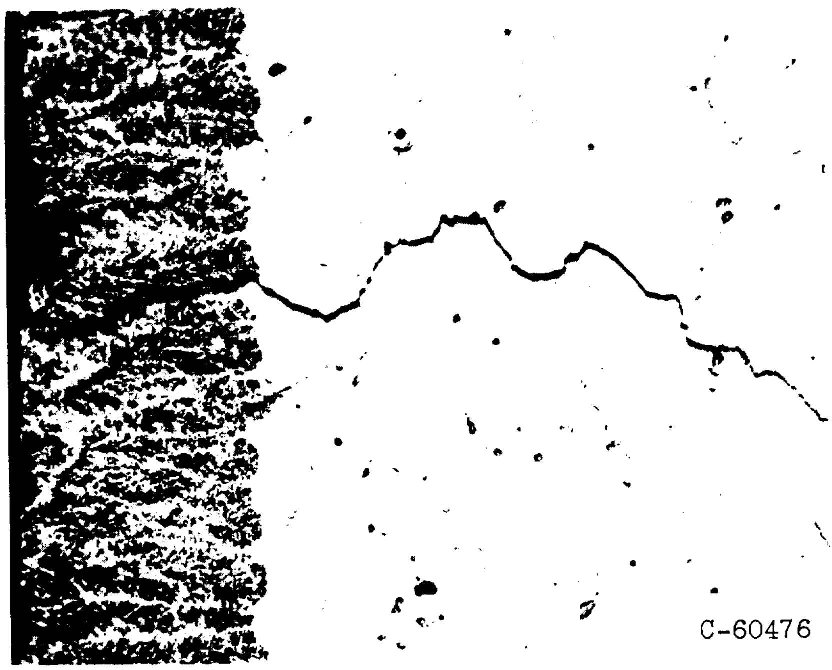


Figure 11. - Thermal-fatigue crack initiated in scale formation on leading edge of NASA alloy bucket. Unetched. ×100.

C-60477

Figure 12. - Heavy scale formation on leading edge of NASA alloy bucket after 224 hours of engine testing. Unetched. ×50.

NASA-Langley, 1962 E-1509